LLNL's Regional Seismic Discrimination Research

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Abstract

The ability to negotiate and verify a Comprehensive Test Ban Treaty (CTBT) depends in part on the ability to seismically detect and discriminate between potential clandestine underground nuclear tests and other seismic sources, including earthquakes and mining activities. Regional techniques are necessary to push detection and discrimination levels down to small magnitudes, but existing methods of event discrimination are mainly empirical and show much variability from region to region. The goals of Lawrence Livermore National Laboratory's (LLNL's) regional discriminant research are to evaluate the most promising discriminants, improve our understanding of their physical basis and use this information to develop new and more effective discriminants that can be transported to new regions of high monitoring interest.

In this report we discuss our preliminary efforts to geophysically characterize two regions, the Korean Peninsula and the Middle East-North Africa. We show that the remarkable stability of coda allows us to develop physically based, stable single station magnitude scales in new regions. We then discuss our progress to date on evaluating and improving our physical understanding and ability to model regional discriminants, focusing on the comprehensive NTS dataset. We apply this modeling ability to develop improved discriminants including slopes of *P* to *S* ratios. We find combining disparate discriminant techniques is particularly effective in identifying consistent outliers such as shallow earthquakes and mine seismicity. Finally we discuss our development and use of new coda and waveform modeling tools to investigate special events.

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Objectives

The ability to negotiate and verify a Comprehensive Test Ban Treaty (CTBT) depends in part on the ability to seismically detect and discriminate between potential clandestine underground nuclear tests and other seismic sources, including earthquakes and mine related events. While large magnitude events can be detected and discriminated teleseismically using well established techniques, events smaller than about magnitude 4.5 may not have adequate signal above the noise to identify definitively. Regional records offer stronger signals and broader frequency content, both of which have the potential to push the identification threshold to a much lower magnitude. However regional methods of event discrimination are mainly empirical and show much variability from region to region. The aim of LLNL's seismic monitoring research is to evaluate the most promising regional discriminants, improve our understanding of their physical basis and use this information to develop new and more effective discriminants that can be transported to new regions. We are applying these regional discriminants in two regions of monitoring interest, the Korean Peninsula and the Middle East-North Africa.

Research Accomplished

As part of the overall Department of Energy CTBT Research and Development program, LLNL is pursuing a broad and comprehensive research effort to improve our capabilities to seismically discriminate potential underground nuclear tests from other natural and man-made source of seismicity. We present here four aspects of this work: Geophysical Characterization, Discriminant Transportability, Improved Discriminants and Special Event Analysis.

Geophysical Characterization

Before beginning to apply regional discriminant techniques to data in an uncalibrated area of the world, several very basic steps need to be taken. These include determining and evaluating some geophysical parameters which are not readily available in the geophysical literature for regions outside of the well calibrated areas of North America, Europe and the nuclear testing sites, where most discriminant studies have been done. Examples include but are not limited to: 1) identifying the regions where the regional phases P_n, P_g, S_n, L_g and the surface waves propagate and where they are blocked; 2) developing a regional magnitude scale consistent with teleseismic magnitude scales and/or physical properties of the events; 3) developing basic regional 1-D velocity models for subregions to predict phase crossovers (e.g. P_n-P_g), relative amplitudes and to locate small events; 4) developing simple frequency dependent attenuation relations for the regional phases to allow a comparison of events at different distances; and 5) building up a ground truth database of known event types in order to begin to evaluate discriminant performance.

To illustrate this process we focus on number (2) above, the example of developing a regional magnitude scale for a new area. It is well known that regional magnitude scales such as $m_b(P_n)$, $m_b(L_g)$, and M_L often differ from each other within a region, with regional magnitude scales in other regions and with teleseismic magnitudes such as m_b and M_s. None of these magnitude scales are based directly on a physical property of the source itself. Recently Mayeda and Walter (1995) have developed a stable single station implementation of the moment magnitude scale, M_w (Hanks and Kanamori, 1979), using coda envelopes. This technique takes advantage of the remarkable stability of coda amplitudes as shown in Figure 1. This figure compares coda amplitudes at two stations (left) with L_g amplitudes at the same two stations for the same set of

Basin and Range earthquakes. The coda amplitudes show more than a factor of 8 less scatter than the direct L_g at 1 Hz, a remarkable result considering that L_g is usually thought of as a fairly stable phase (e.g. Hansen et al., 1990). This stability means that we achieve the same accuracy of magnitude estimation with a single station as a network of well distributed stations using L_g. Because moment is a physical quantity, moment magnitude can be compared with moments in other regions directly. We have used the technique to estimate events as small as M_w=2.2, with the lower limit determined only by signal above the noise of the regional coda.

We recently applied this coda magnitude technique to a small set of events recorded at a single 3-component station on the Korean Peninsula. It requires a small set of events covering a range of distances which are used to determine the coda attenuation properties to obtain path and relative site corrections. We then determine the moment of several of the larger events using a waveform modeling technique (Walter, 1993) to calibrate the scale and make an absolute site correction. The waveform modeling also directly contributes to the geophysical characterization since it allows an evaluation of published 1-D velocity structures and event locations. The waveform modeling also allows us to begin to build up a ground truth database since we can use it to begin to identify the larger events via their depth and focal mechanism. We illustrate the coda magnitude results in Figure 2 for the few events we have that were large enough to have teleseismic m_b magnitudes or for which we determined moments. Note that the coda based magnitudes correlate better with these independent results than a more simplistic regional magnitude scale based on the amplitude of P_g.

Discriminant Transportability

The general increase in seismicity on the Nevada Test Site (NTS) following the Landers M_w=7.3 earthquake on June 28, 1992 along with the historical database of underground nuclear tests forms a nearly ideal dataset for studying the physical basis of earthquake-explosion discrimination. Figure 3 shows the location of these events and illustrates an example of the type of earthquake-explosion difference in the high frequency L_g phase typically observed. We are doing a two part study of discrimination using this dataset. We have recently completed the first part, an empirical study of the most promising small magnitude discriminants (Walter et al., 1995). We are working on the second part, improving our physical understanding of regional discriminants. We approach this problem by modeling the path corrected regional phase spectra as the product of a source spectrum with a transfer function spectrum. The transfer function spectrum represents the near source scattering efficiencies of phase conversions, particularly P to S and R_g to S conversions. Then we model the dependence of the source time function on the material properties at the shot point. We also model the frequency dependence of the transfer function on the depth, mechanism and material properties of the event. An example is shown in Figure 4. where we have successfully matched the general behavior of the high/low spectral ratio discriminant for L_g. This type of physically based modeling ability is crucial to understanding where and under what circumstances a discriminant may fail, especially when it is transported to regions outside of where it was developed and empirical data are insufficient to fully validate it.

Improved Discriminants

As a result of our NTS discrimination work we have begun developing new discriminants that are more effective at separating particular types of events from the explosions. In the original study (Walter et al., 1995) we noted that the *P/S* ratios P_n/L_g and P_g/L_g appeared to show much variability between the two stations examined, MNV and KNB. While the discrimination

performance improved as the frequency band increased, even at the highest band for reasonable signal, 6-8 Hz, the P_n/L_g discriminant shows many overlapping events, particularly for the shallow earthquakes at station KNB as shown in Figure 5a. We also noted the *P/S* ratios showed the explosion material dependence was the opposite of the spectral ratios shown in Figure 3. Averaging over stations and taking a simple product of these phase and spectral ratios discriminants to reduce the material property dependence, we improve the discrimination performance greatly (Figure 5 b). Shallow earthquakes still remain somewhat problematic.

Another type of regional discriminant that shows promise is based on comparisons of moment to magnitude (Patton and Walter, 1993; Woods et al., 1993). This is a regional extension of the traditional long-period:short-period discriminants like $M_s{:}m_b$ but is not limited only to those events large enough to generate surface waves. Moment can potentially be measured on any size event. We are presently investigating techniques to measure moment using the very stable coda methods described in the Geophysical Characterization section. In our initial studies $M_o{:}m_b(P_n)$ appears to have the potential to correctly classify shallow earthquakes, but it appears to have trouble with mine collapses as shown in Figure 5c (Patton and Walter, 1994). Note that mine collapses are correctly classified in the 6-8 Hz P_n/L_g ratios in Figure 5a.

Discrimination studies in a variety of regions have shown that explosion *P/S* ratios tend to increase and discrimination improves as frequency increases (e.g. Scandinavia: Dysart and Pulli, 1987, Baumgardt et al, 1992; Central Asia: Bennett et al, 1989; Eastern U.S.: Kim et al; Western U.S.: Walter et al., 1995; and others). These observations suggests that this increasing slope of *P/S* may be useful as an identifier of explosions. Goldstein (1995) has developed this idea as a discriminant by examining the slope of the P_n/L_g ratio for the NTS data plus other western U.S. earthquakes. The *P/S* slope results as shown in Figure 5d are quite good, only a few events are misclassified and this discriminant appears to have the best single station performance of those tested. Of particular interest is the improvement in the correct classification of the shallow earthquakes compared with the direct P_n/L_g ratio in Figure 5a. The overall impression in comparing these disparate discriminants in Figure 5 is that because they have different outliers, combinations of discriminants may offer the best hope of improving event identification.

Special Event Analysis

Events that fail one or more discriminants ("special events") may require a more detailed investigation to positively identify. In addition they offer the opportunity to learn more about the physical basis of a particular discriminant by demonstrating how it can fail. As discussed above these are often shallow events with unusual mechanisms. In order to understand some of these persistent special events, namely mine blasts and mine collapses we are carrying out a field program to record and study both of these types of events in detail.

We have been investigating the use of two tools to help identify and understand special events. The first is the coda derived source spectra. While normal depth earthquake spectra have a typically constant low frequency level and rolloff above a corner frequency, unusually shallow events have peaked spectra as shown in Figure 6. The frequency of this peak, at least for explosions scales with absolute depth of burial. In addition, for events with non-earthquake mechanisms the spectra appear to decrease significantly from the peak as frequency decreases. We believe this peaking and rolldown is related to the Rayleigh wave excitation which is a function of depth, velocity structure and mechanism.

We have also had good success using waveform modeling techniques (e.g. Walter, 1993) for large events with unusual mechanisms. If the event has detectable surface waves and a reasonable 1-D velocity structure is known, it is possible to discriminate between a collapse and an explosion using the phase of the Rayleigh waves. Ruling out an earthquake is more difficult but if sufficient azimuthal coverage is available, the presence or lack of Love waves can be used. This process is shown in Figure 7. We used this method with good results on two recent large mine collapses, one in Wyoming (Pechmann et al., 1995) and one in the Ural region of Russia.

Conclusions and Recommendations

LLNL is making good progress in characterizing regions of monitoring interest as well as in evaluating and understanding the regional discriminant behavior. We have used this information to develop improved discriminant techniques. Combining different regional discriminants appears to have the potential to achieve very high rates of event identification and discrimination. We are continuing to develop new tools and collect field data to study special events (outliers on discriminant plots). We are optimistic that combining all this information will make discriminant transportability practical, even in regions that presently have little ground truth data.

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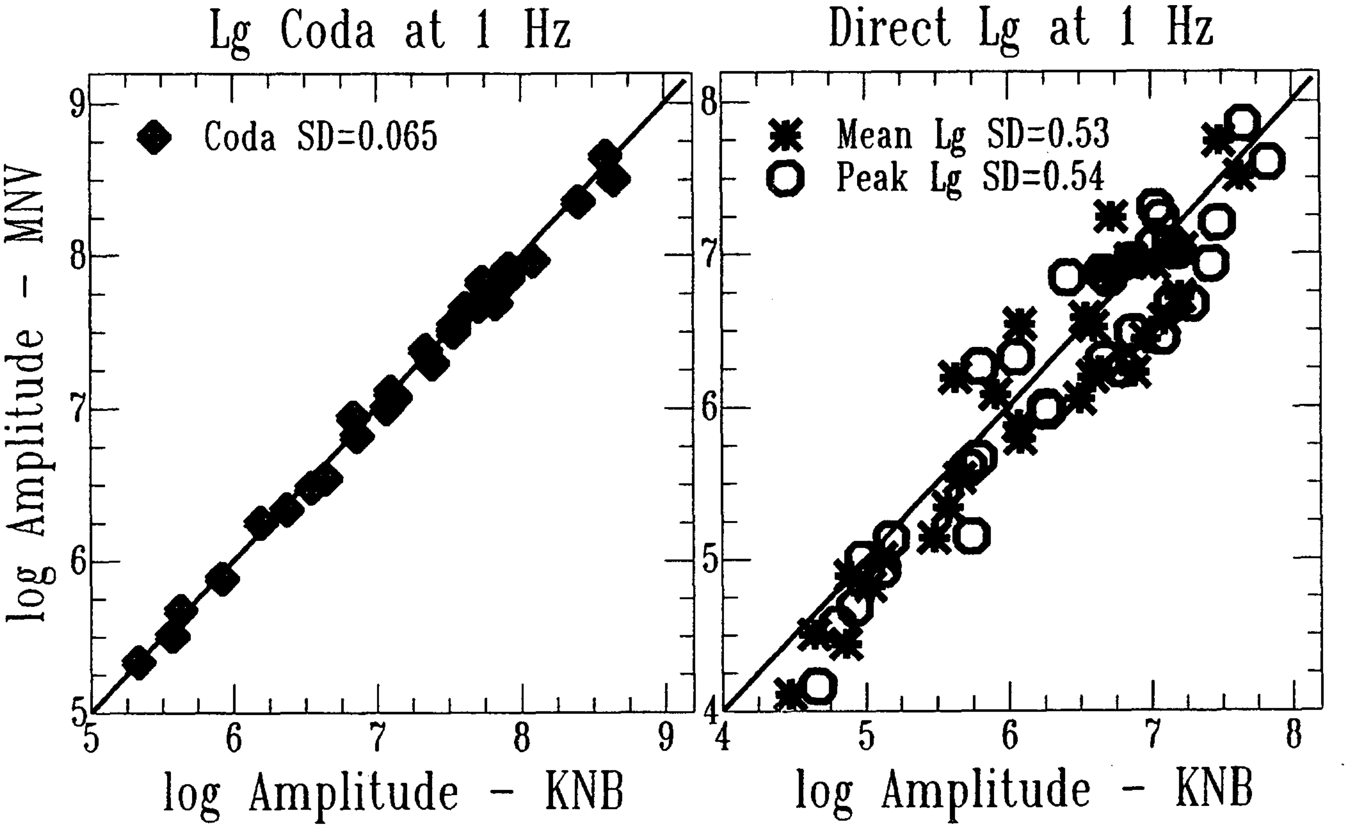

Fig. 1. A comparison of the interstation stability of amplitudes determined from coda with those determined from the direct L_g phase. The regional coda amplitudes are 8 times more stable than direct L_g at 1 Hz, as indicated by the standard deviation from the line. We use this stability to obtain accurate single station estimates of seismic source parameters such as the moment magnitude, M_w (Mayeda and Walter, 1995).

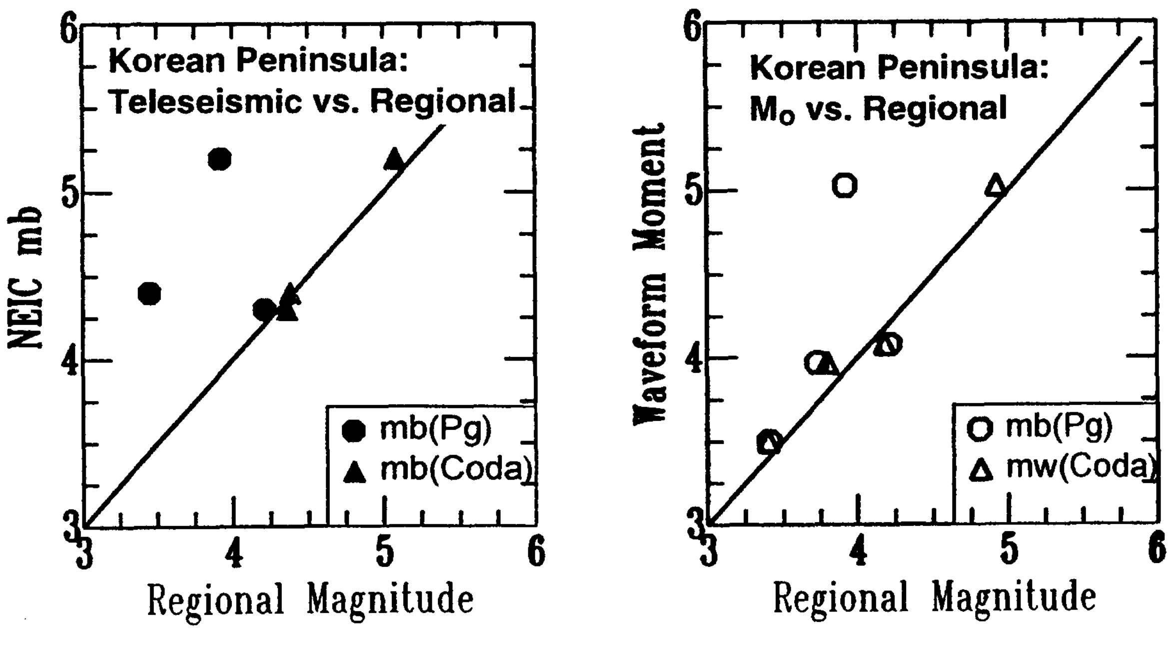

Fig. 2. Preliminary results show the stability of calibrated, single station coda magnitudes are transportable to the Korean Peninsula. The coda results correlate better with independent estimates of size than those based on the amplitude of regional phase P_g. Moments are estimated from regional waveform modeling.

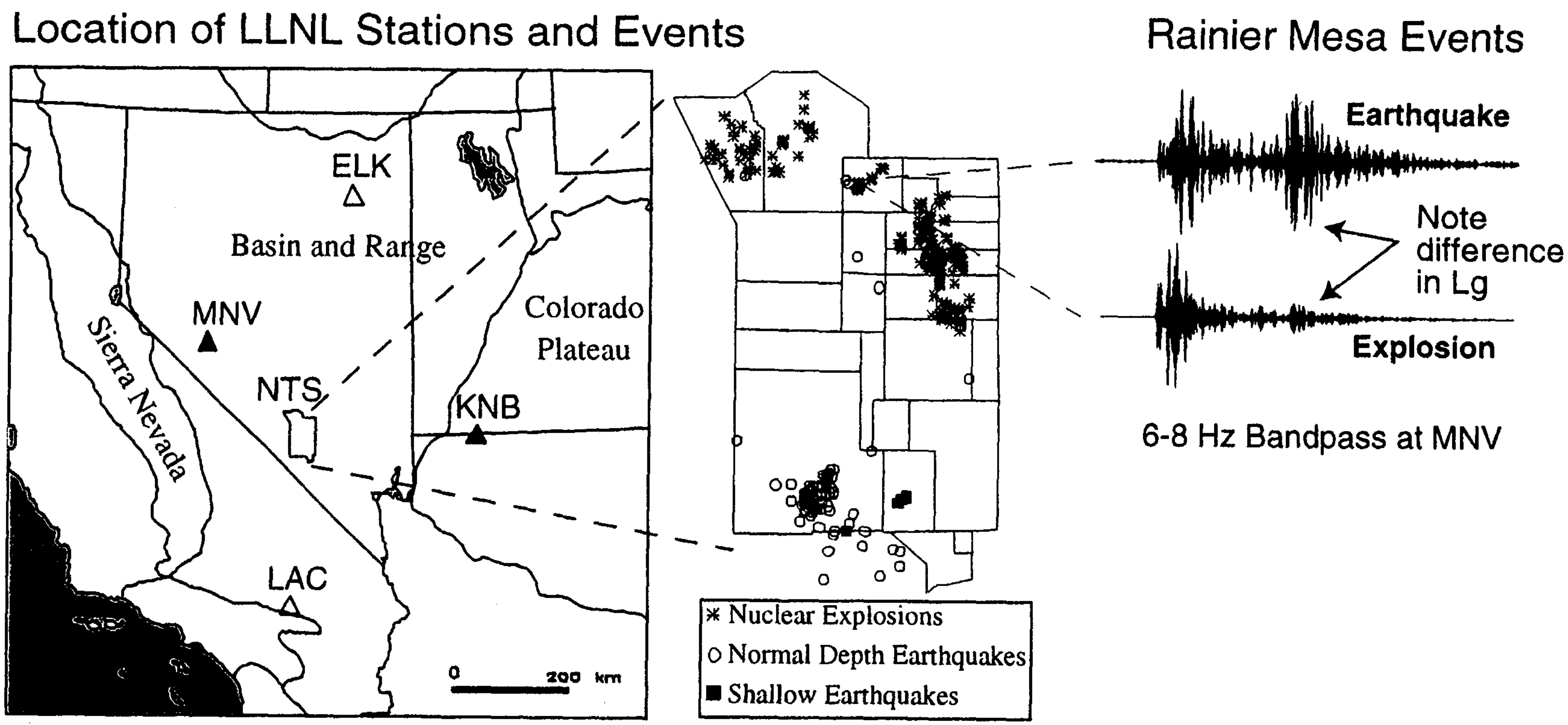

Fig. 3. NTS events form a nearly ideal data set for examining the physical basis of earthquake-explosion discrimination. Map on left shows the locations of NTS and the stations that recorded these events. Center map shows location of earthquakes and explosions at NTS. Right hand traces show the differences in high frequency recordings of a similar sized earthquake and explosion with similar epicenters and magnitudes. Because of the similarity of the paths we can ascribe the observed differences in L_g to depth, mechanism, source time function and material property differences. The data cover a range of depths, magnitudes, mechanisms and material properties allowing us to evaluate the relative importance of each for discrimination.

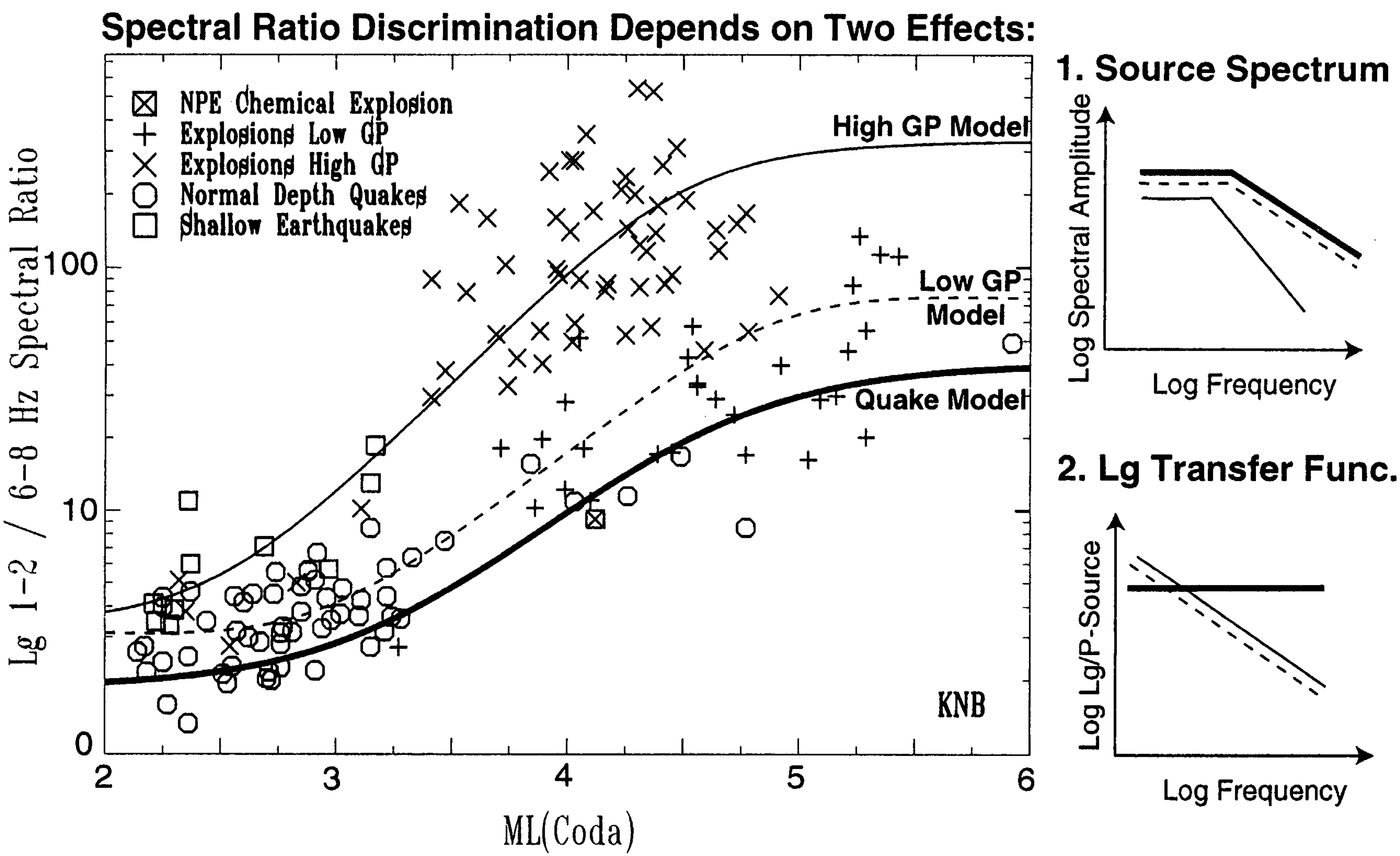

Fig. 4. A model for the L_g low/high or (1-2 Hz)/(6-8 Hz) spectral ratio discriminant. We model the path and site corrected L_g spectrum as the product of source and transfer function terms. Each of these terms is modeled as follows: 1) source spectrum sensitivity to material property effects as illustrated on the upper right. Explosions in high gas porosity low strength materials have source spectra with steeper high frequency falloff than earthquakes or low gas porosity explosions. 2) transfer function (frequency dependent measure of S source plus $P+R_g$ scattering into S) is nearly constant for earthquakes but varies strongly for explosions.

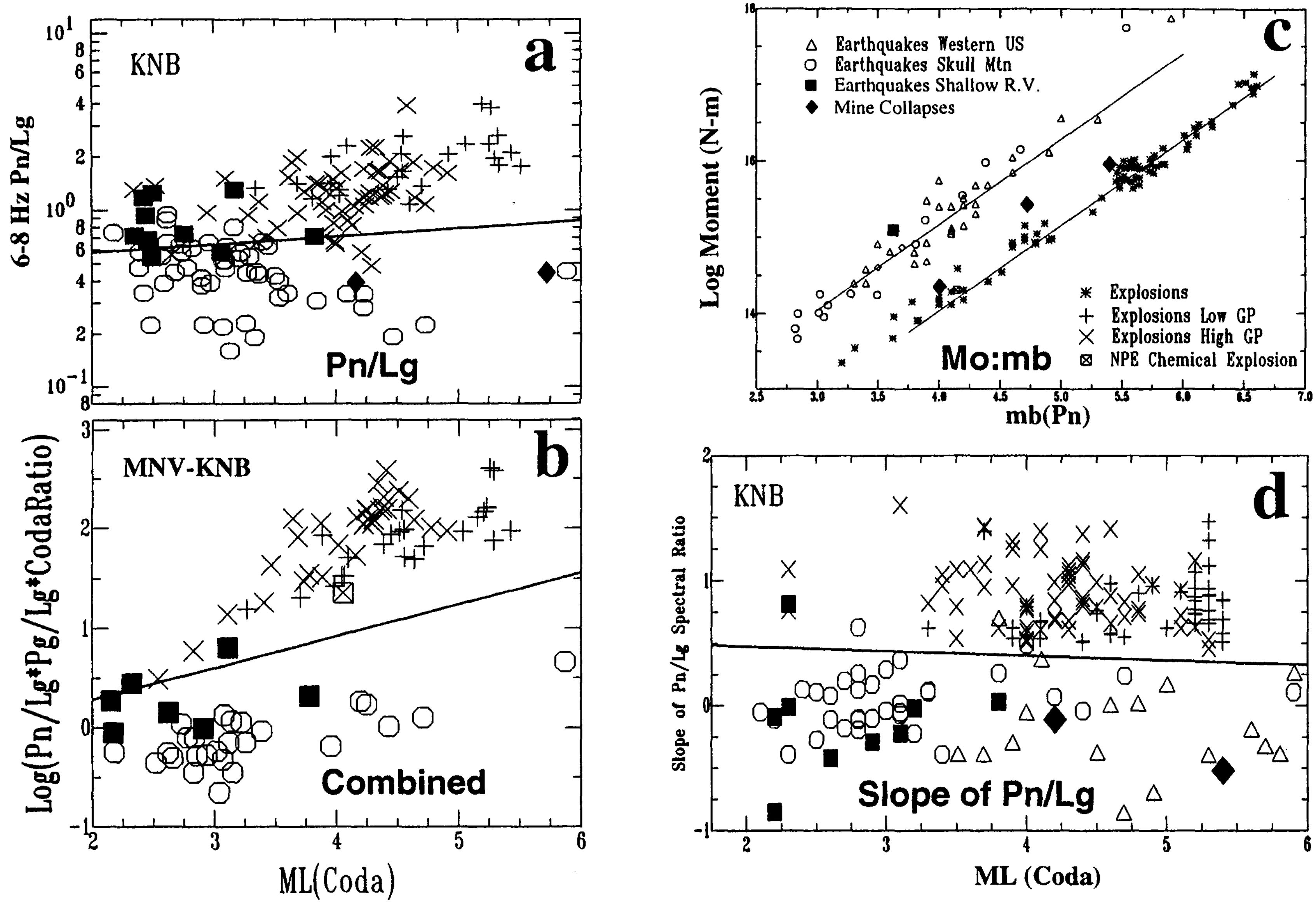

Fig. 5. A comparison of regional discriminants in the western U.S. (a) 6-8 Hz P_n/L_g at KNB (Walter et al., 1995). (b) Combined 6-8 Hz P_n/L_g, P_g/L_g and 1-2/6-8 Hz L_g coda ratio averaged for MNV-KNB (Walter et al., 1995). (c) Regional M_o versus $m_b(P_n)$ (Patton and Walter, 1993). (d) Slope of P_n/L_g at KNB (Goldstein, 1995). Note shallow earthquakes (filled squares) are a problem for (a) and (b) but not (c) and (d), while collapses are a problem for (c) but not (a) and (d). Combinations of regional discriminants can best identify events.

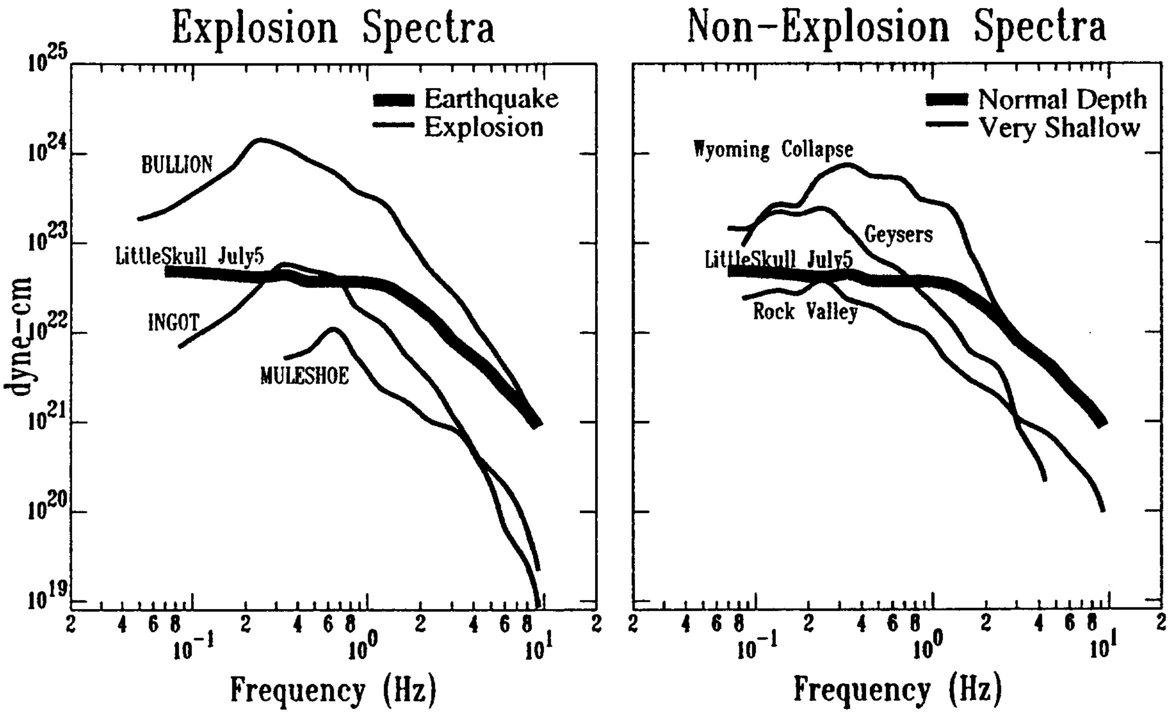

Fig. 6. Coda derived source spectra compared for a normal depth earthquake and a variety of very shallow events. Note the normal depth earthquake source spectra looks simple: constant at long periods and falling off above a corner frequency. In contrast the shallow events when processed in an identical manner look unusual and are peaked. The frequency of the peaked spectra scales with absolute depth for explosions.

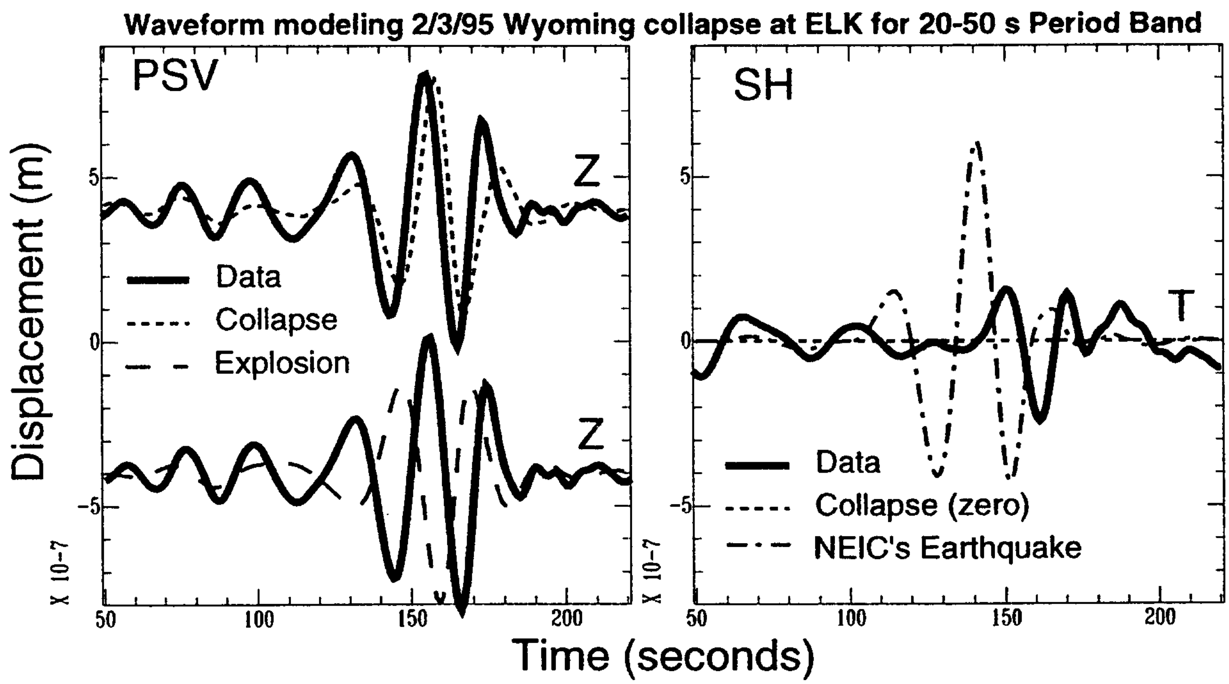

Fig. 7. Intermediate period waveform modeling can identify seismic source when the path is known. Explosions and earthquakes can be distinguished at one station on the basis of their Rayleigh wave phase as shown on the left. Ruling out an earthquake is more difficult and requires at least two stations with differing azimuths. The presence or absence of Love waves is then an indicator of whether the event was an earthquake.